

<b>Institution:</b> University of Southampton
<b>Unit of Assessment:</b> 07 Earth Systems & Environmental Sciences
<p><b>1. Unit context and structure, research and impact strategy</b></p> <p><b>1.1 Overview</b></p> <p>The submission returns 67 staff (60.0 Full-time equivalent, FTE, 49M/18F) from the School of Ocean and Earth Science (SOES), part of the Faculty of Environmental and Life Sciences (FELS). SOES staff and research facilities are co-located with the National Oceanography Centre (NOC), a newly-independent self-governing organisation, at the National Oceanography Centre Southampton (NOCS), on the University's Waterfront Campus. NOCS is a leading global centre of excellence for research, education, technology development, knowledge transfer and innovation in the Ocean and Earth Sciences.</p> <p>SOES has a distinctive profile of research aiming to develop a fundamental understanding of the whole Earth system, and to apply new knowledge to ensure the future sustainability of our planet.</p> <p>Major achievements since REF2014 include:</p> <ul style="list-style-type: none"> <li>• Recognition of our world-leading expertise in the marine and maritime sector through the award in 2016 of a Regius Professorship in Ocean Sciences by HM The Queen.</li> <li>• Publication of a substantive body of world class outputs, with an overall Field Weighted Citation Impact (FWCI) of 1.92 and &gt;45 publications in key interdisciplinary journals (Nature, Science, PNAS).</li> <li>• Significant impact through major scientific firsts including: demonstration of permanent carbon capture and storage in Icelandic basalt rocks; using innovative tools to identify underground fluid injection depth as a driver for induced seismicity magnitude; novel observations of sub-mesoscale ocean turbulence and its impacts using autonomous robots.</li> <li>• Playing a leading role in international ocean-going science with 20 Category A staff (12M/8F) spending an average of ~70 days at sea (combined &gt;1300 days), providing 9 principal scientists for NERC and international cruises and 5 Co-Chief scientists for the International Ocean Discovery Programme (IODP, the largest number for any UK HEI).</li> <li>• Continued development of a diverse, well-supported, collegiate international researcher community, including: recruitment of 8 new staff (4M/4F, 50% Early Career Researchers; ECRs) and 4 Independent Research Fellows (2M/2F), 16 associate professor (10M/6F) and 14 full professorial (11M/3F) promotions, and the graduation of 264 PhD students from the NOCS graduate school (run collaboratively with NOC).</li> </ul> <p><b>1.2 Research Strategy</b></p> <p>Our 2014-2020 Research and Impact Strategy aimed to deliver <u>world-class fundamental and applied research addressing key environmental and societal challenges in Marine and Earth Sciences</u>. Tackling emergent interdisciplinary challenges necessitates a strategy embedding our core principles of <i>excellence</i>, <i>capacity</i>, <i>sustainability</i> and <i>agility</i> into all research activities.</p>

Our strategy is built on:

- i) Recruiting and developing diverse staff, fully supported in their research activities and well-being in a collegiate environment;
- ii) Establishing and maintaining state-of-the-art facilities, sustaining research-income and recruiting, supporting and training a vibrant postgraduate researcher community;
- iii) Capitalising on synergies between the educational, research, enterprise and impact activities of SOES and our partners, to deliver a stimulating and supportive environment promoting intellectual development and timely world-class innovation.

SOES is structured into six research groups: (a) Geochemistry (GC; 11M/4F), (b) Geology and Geophysics (G&G; 8M/6F), (c) Marine Biogeochemistry (MB; 5M/4F), (d) Marine Biology and Ecology (MB&E; 10M/3F), (e) Palaeoceanography & Palaeoclimate (P&P; 10M/1F), and (f) Physical Oceanography (PO; 5M). All SOES research staff have a primary association with one of these research groups while engaging in trans-disciplinary research across the groups, the wider University of Southampton (UoS), and a broad range of national and international research organisations (see §1.6 & 4.1). Major research areas within SOES are closely aligned with two UoS Strategic Interdisciplinary Research Institutes (USIRIs): the Southampton Marine and Maritime Institute (SMMI), which serves as a gateway for industry, government and civic bodies, and international collaborators to the maritime and marine expertise of UoS, and the Institute for Life Sciences (IfLS) which integrates bioscience research across UoS (see REF5a §2.6).

Research, enterprise and impact strategies and decisions are facilitated through regular research group meetings, whole school 'away days', our dedicated Enterprise units and the SOES Research and Enterprise Strategy Group composed of research group heads (currently 3M/3F: **Foster-GC**, **McNeill-G&G**, **Lam-MB**, **Godbold-MB&E**, **Wilson-P&P**, **Haigh-PO**) and the Deputy Head of School Research and Enterprise (**James**; F) and the Director of Enterprise (**Dix**; M).

### 1.3 Achievement of strategic aims 2014-2020

Our overarching aim to 'lead international research in oceanography and marine geoscience' has been delivered through sustained research funding (see §3.1) for national and international collaborative interdisciplinary projects (see §3.4 & 4.1) that have produced world class outputs, with ~25% of our publications ranked in the top 10% in terms of citations with an overall FWCI of 1.92. Our specific aims were to:

- *Develop and apply new geophysical imaging techniques (G&G, GC, SMMI)*

Supported by >£7M, we led innovative applications of an array of geophysical techniques to answer major questions in the Earth Sciences including: the nature of the lithosphere-aesthenosphere boundary (**Rychert, Harmon**), the processes of continental rifting and subduction (**Minshull, Bull, Keir, Gernon, McNeill, Henstock, Rychert, Harmon**), and suspended sediment dynamics in submarine gravity currents (**Sumner**). We tackled societal problems including offshore carbon capture and storage (**Bull, Minshull, Henstock, Gehrmann**), substrate controls on offshore marine HV cable installation and operation (**Dix, Henstock, Gernon**), the impacts of space weather on electromagnetic fields (**Simpson**), sustainable deep-sea mining (**Minshull**), and the controls on human induced seismicity (**Gernon, Hincks**). We also led the geo-components of one of the largest ever underwater marine archaeological investigations (**Dix**).

- *Investigate the processes determining the rate, structure and climatic role of the global overturning circulation (PO)*

We attracted >£3M for major projects investigating global overturning circulation (e.g. DynOPO, MerMeed and BLT Recipes, **Naveira-Garabato**) and its climatic impacts (e.g. SMURPHS and Blue Action, **Drijfhout**), resulting in significant advances in process understanding (**Naveira-Garabato, Oliver**), links to ongoing global climate change (**Skliris; Drijfhout**) and new approaches to climate predictability (**Sévellec, Drijfhout**). We led the development of a major (£7M) NERC Strategic Research Programme (RoSES, **Naveira-Garabato**) addressing key uncertainties in the Southern Ocean carbon sink, and made important contributions to the Intergovernmental Panel on Climate Change (IPCC) 6<sup>th</sup> Assessment Report (AR6; **Drijfhout** is lead author of the Ocean, sea level and cryosphere chapter).

- *Determine the impact of the retreating cryosphere on ocean circulation, sea level and climate variability (PO, P&P, GC)*

We discovered new processes governing ocean-Antarctic ice sheet interaction (**Naveira Garabato**), improved the representation of icebergs in global-scale ocean models (**Marsh, Skliris**), and developed novel approaches for the detection and prediction of changes in the rate of sea level rise (**Goodwin, Haigh**), with contributions extensively cited in the IPCC Special Report on the impacts of global warming of 1.5°C (2018). We explored the role of Mediterranean Outflow Water in driving Northern Hemisphere glaciations (**Xuan**) and studied past climates to quantify the instability of continental ice sheets under warmer-than-present conditions (**Bohaty, Ezard, Foster, Kemp, Rohling, Wilson**). We secured £2M for major projects improving iceberg forecasting for safer operations at sea (e.g. ICECAST and SOS-SOS, **Marsh**), advancing understanding of compound flooding (e.g. CompFlood and CHANCE, **Haigh, Marsh**), and determining optimal strategies for mitigating the adverse effects of global sea level rise (e.g. E-Rise, **Haigh** and ADJUST1.5, **Goodwin, Haigh**).

- *Study carbon cycling, climate sensitivity and biotic change in past and future high CO<sub>2</sub> worlds (P&P, GC, MB&E)*

We used innovative approaches and novel palaeo-data to reduce the uncertainty of future climate projections (**Goodwin, Foster, Rohling**) and demonstrate that climate sensitivity during past warm intervals was in the IPCC range (1.5 to 4.5 C per CO<sub>2</sub> doubling; **Foster, Rohling**). We revealed that changing atmospheric CO<sub>2</sub> concentration was the primary driver of early Cenozoic climate (£1M, The Descent into the Icehouse; **Foster, Inglis**), and secured >£3M for an interdisciplinary project, PISTON, to investigate the fundamental processes by which new species emerge (**Ezard, Wilson, Foster, Trueman**). We made major contributions to understanding the environmental causes, consequences and recovery from the end-Cretaceous (**Gibbs, Wilson, Whiteside**), end-Triassic (**Whiteside**) and end-Devonian (**Marshall**) mass extinctions. We also showed that rapid carbon release from the oceans drove the rise of CO<sub>2</sub> during the last deglaciation (**Foster, Palmer, Cooper**) and extensively contributed to the forthcoming IPCC AR6 (**Foster** is contributing author on two chapters).

- *Investigate the biogeochemical evolution of Earth surface processes (GC, G&G, MB, MB&E)*

We utilised novel analyses to identify the role of hydrothermal circulation in seafloor mineralisation (**Roberts**) and quantified its control on the thermal and chemical exchange between the ocean crust and seawater, underpinned by a major international ocean drilling

campaign (**Coggon, Teagle**). We quantified weathering-climate linkages in the past (**James, Wilson, Gernon**) and investigated enhanced weathering and mineral carbonation as CO<sub>2</sub> removal methods (>£1.5M; NERC-funded strategic programme on Greenhouse Gas Removal, the Leverhulme Centre for Climate Change Mitigation, and industry sources; **James, Lam, Teagle, Matter**). We advanced the understanding of volcanic processes (**Gernon, Palmer, Taylor**) and the linkages between volcanism and global mass extinctions (**Whiteside, Wilson**).

- *Investigate biogeochemical cycles and their response to climate change (MB, MB&E)*

We demonstrated new processes governing the cycling and interactions of oceanic macronutrients (**Lam, Purdie, Tyrrell**) and micro-nutrients (**Bibby, Lohan, Moore**), uncovering links between marine microbial eco-physiology (**Bibby, Brownlee, Hickman, Lam**) and carbon cycling (**Moore, Tyrrell, N.Bates, Trueman, Lucas**). We led major projects (>£4.5M) to investigate how oceanic CO<sub>2</sub> sequestration and other ecosystem functions are impacted by carbon and nutrient cycling, microbial ecology and ocean productivity (e.g. SONiC, **Lam**; COMICS, **Lam, Moore**; RoSES/CUSTARD, **Moore, Bibby**; ZIPLOc, FeRidge, **Lohan**; S3-EUROHAB, **Purdie**; I/URFs: **Ward, Annett**). We led the £3M pelagic component of the UK Ocean Acidification Research Programme (UKOARP) (**Tyrrell, Moore**) and were major contributors to the pelagic (**Hickman, Moore, Purdie, Tyrrell**) and iron cycling (**James, Lohan, Mills, Statham**) components of the NERC Shelf Seas Biogeochemistry (SSB) programme (>£4M overall).

- *Investigate the importance of sediment dynamics in biogeochemical processes (G&G, MB&E, SMMI)*

We led the £3.5M benthic component of the NERC SSB programme (**Solan**), demonstrating how seasonal changes and geographical variability are fundamental to the functioning of UK Shelf Sea systems, highlighting the impacts of intensifying human activities (**Godbold, Thompson, Solan**). We investigated how changing sea-ice conditions impact biological communities and sediment biogeochemical processes in Arctic sediments (ChAOS, **Solan, Godbold**). We also played a key role in a major NERC-funded project on monitoring seafloor sediment avalanche dynamics using novel in situ instrumentation, demonstrating their importance for organic carbon burial (**Sumner**).

- *Establish relationships between anthropogenically forced environmental change, biodiversity loss and ecosystem processes to inform sustainability (MB&E, SMMI, IfLS)*

We demonstrated the impact of climate change on harmful invasive species in UK waters, including through the use of novel eDNA technology (**Hauton, Rius, Solan**). We promoted poverty alleviation through prevention and future control of pathogens in Asian shrimp aquaculture (**Hauton**). We elucidated the fundamental mechanisms by which oceanic inorganic nutrients affect the growth and resilience of coral reefs (**D'Angelo, Wiedenmann, Wilson**). We secured £2M to investigate the impact of non-traditional pollutants such as microplastics (MINIMISE, **Godbold, Solan**), artificial light (ALICE, **D'Angelo, Wiedenmann**) and sound (US Office of Naval Research grant, **Solan**) on coastal and shelf ecosystems. We detailed the importance of habitat continuity in shaping coastal diversity (**Fenberg**) and realised new biomimetic marine infrastructures to improve the ecological status of coastal waters and their role in coastal recovery (MARINEFF, **Hauton, Collins, BLUE-coast, Solan, Godbold, Thompson**). We investigated the ecological impacts of deep-sea mining (**Copley, Hauton**) and the effects of intense fishing on the management and conservation of threatened oceanic animals (**Sims**).

#### 1.4 Research objectives 2021-2026

Our overarching aim is to deliver ground-breaking knowledge on fundamental scientific problems in the Ocean and Earth System, and to apply this new knowledge to address emerging environmental and societal challenges and inform action to mitigate the effects of climate change. Specifically, we will:

- *Reduce uncertainty in the climate system and climate models (PO, P&P, GC)*

We will integrate efficient Earth system models with new palaeo-data to inform mitigation efforts needed to meet climate targets, explore tipping points in the carbon cycle and climate system, and quantify the response of the cryosphere and hydrological cycle to warmer-than-present past climate states.

- *Develop and test solutions for greenhouse gas emission reduction and atmospheric removal (G&G, GC, MB, SMMI)*

We will explore the viability of methods for CO<sub>2</sub> removal from the atmosphere, including enhanced weathering, mineral carbonation and ocean alkalisation. We will determine the potential of CO<sub>2</sub> leakage from sub-seafloor storage reservoirs and will research: the potential of marine algae as a biofuel, geothermal energy sources and HV cable deployment, and quantify the environmental impacts of such clean energy solutions and infrastructures.

- *Evaluate the sustainability of natural resources on land and in the oceans (MB&E, GC, MB, G&G, SMMI)*

We will develop novel techniques to find new sources of metals and elements critical to emerging “green” technologies. We will investigate the impacts of deep-sea resource utilisation on marine organisms and ecosystems, use novel chemical techniques to provenance natural resources (e.g. fisheries, radionuclides) and explore the impact of disease on aquaculture for food sustainability.

- *Investigate the impacts of natural change and anthropogenic stressors on marine ecosystems and biogeochemical cycles (MB&E, MB, GC, P&P, IfLS)*

We will provide new understanding of oceanic carbon and nutrient cycling and quantify the response and vulnerability of open ocean and coastal ecosystems (e.g. coral reefs) to recognised and emerging stressors (including light pollution, inorganic nutrient inputs, sound). We will apply novel molecular techniques to investigate microbial community interactions and the mapping of marine invasive species.

- *Manage chemical risks in the environment (GC, MB, MB&E)*

We will study the processes that determine the fate of radionuclide and other contaminants in terrestrial, atmospheric and aquatic environments. We will determine contaminant ecotoxicology and assess the interactions of contaminants with other stressors on ecosystem functioning and services.

- *Develop new technologies and strategies for increasing resilience to environmental hazards (PO, G&G, MB&E)*

We will use Earth observations, data monitoring, and numerical models to forecast and improve understanding of the frequency, severity, and interactions of natural hazards, from coastal, fluvial and pluvial flooding events to explosive volcanic eruptions and earthquakes.



- *Investigate connections between plate tectonics, mantle dynamics and natural hazards (G&G, GC, P&P)*

We will use a wide range of geological and geophysical methods, including ocean drilling, to improve our understanding of the evolution and connectivity between Earth's tectonic systems, the dynamics of the deeper mantle, surface geological hazards and the drivers of natural climate change.

- *Digital Planet – Environmental data to knowledge (GC, G&G, PO, MB, SMMI)*

We will develop techniques for the collection and real-time analysis of high spatial/temporal resolution data using autonomous systems (e.g. utilising extant fibre-optic monitoring systems for ocean bottom temperature, autonomous underwater vehicles for water properties).

Delivery of these objectives will be supported by:

- i) *Continued development of an excellent diverse and agile researcher base:* We will increase academic staff numbers to 65FTE through hiring into the priority areas above and by building on our success in transitioning independent fellows to permanent contracts (4 during current REF period: **Goodwin, Gibbs, Hickman and Hain**; 2M/2F). We will continue to train the researchers of tomorrow through the NOCS Graduate School (GSNOCS) and leadership of the INSPIRE Doctoral Training Partnership (DTP).
- ii) *Sustainable and diversified income:* We will attract UKRI funding and independent research fellowships, while further diversifying our funding streams, capitalising on new initiatives (e.g. Strategic Priorities Fund) and expanding our enterprise and knowledge transfer activities to become a significant part of our funding portfolio.
- iii) *Maintaining world class facilities:* Strategic facility investments and space allocation will support changes in our portfolio resulting from recruitment (i) and income generation (ii).

### 1.5 Facilitating impact

We promote knowledge transfer to industry, public bodies and the third sector through the activities of the SOES Stakeholder Advisory Board, which includes representatives from BP, Lloyds Register, Halliburton and the Centre for Environment, Fisheries, and Aquaculture Science (Cefas), and is chaired by **Townend**, formerly Research Director of HR Wallingford. Recent activities have focused on designing impactful research projects, identifying major research challenges, and stakeholder involvement in education delivery. Our impact strategy is supported and facilitated by wider University activities (REF5a §2.9) and by stakeholder participation in the design and operation of our INSPIRE DTP (e.g. Met Office, Centre for Ecology and Hydrology (CEH), HR Wallingford, Autonomous Robotics Ltd, JNCC, Lloyds Register, Thales).

All SOES research groups offer expert services with many of our world-class research facilities available for external use, supporting a diverse portfolio of enterprise activities, from quantification of trace metal contamination in contact lenses (for the UK's largest contact lens manufacturer, CooperVision) to assessing the efficacy of anti-corrosion coatings on naval vessels for BAE Systems. Two dedicated enterprise units, GAU-Radioanalytical, and Coastal and Offshore Archaeological Research Services (COARS), provide the major focus for SOES enterprise activities (see §3.1).

The effectiveness of our impact strategies is illustrated by our selected REF2021 Impact Case Studies (ICSs):

**ICS1:** Deep Impact: engaging public audiences and policymakers with the exploration and stewardship of biodiversity in the deep ocean (**Copley, Mills**);

**ICS2:** Rising Tide: Informing management, planning and policy on acceleration of sea level rise, increased coastal flooding and changes in tide (**Haigh**);

**ICS3:** Translating Coral Reef Science into Industry Products, Educational Initiatives, and Public and Stakeholder Awareness (**D'Angelo, Wiedenmann**);

**ICS4:** Environmental Optimisation of Marine High Voltage Cable Design, Installation and Operation (**Dix, Henstock, Gernon, Thompson, Bull**);

**ICS5:** Difficult to measure (DTM) radionuclide characterisation supporting nuclear decommissioning and environmental monitoring (**Warwick, Cundy**).

Collectively, these ICSs include knowledge transfer from ongoing research and enterprise activities to: industry (ICSs 4, 5); public bodies (ICSs 1, 2, 5); the third sector (ICSs 1, 2, 3); and the general public (ICSs 1, 2, 3). The success of our strategy is further evidenced by a broader impact portfolio including: development of algal biotechnology (**Bibby**, FeedAlgae UK); commercial sensor development (**Moore**, Chelsea Technologies UK); hydrocarbon exploration (**Marshall**, Andina, BG, Chaco, PanAmerican, Repsol, Shell); traceability in wild catch fisheries (**Trueman**, Marine Stewardship Council, Marine Management Organisation, Young's Seafood); disease management in Asian aquaculture (**Hauton**, ICAR Central Institute of Brackish water Aquaculture and ICAR National Bureau of Fish Genetic Resources, India; Marine Products Export Development Authority and Ministry of Commerce & Industry, Government of India); and supporting safety at sea (**Marsh & Skliris**, Lloyds Register, Met Office).

### 1.6 Supporting interdisciplinary research

Interdisciplinarity is built into the breadth of our six SOES research groups, the SOES-NOC partnership, and the inter/multi-disciplinary PhD supervisory teams and training activities which drive the postgraduate research programmes of GSNOCS, the UoS Doctoral college (REF5a §3.7) and the SOES-led NERC DTPs SPITFIRE (2014-2019) and INSPIRE (2019-2024). Our leadership of GSNOCS and the DTPs generates collaboration across UoS (e.g. with archaeology, biology, chemistry, engineering and medicine) as well as with our DTP host partner organisations (NOC, British Antarctic Survey (BAS), Marine Biological Association (MBA) and Natural History Museum (NHM)) and a range of CASE and collaborative partner organisations including the Met Office, British Geological Survey and CEH (<http://projects.noc.ac.uk/inspire/partners>), other leading universities, NGOs, and research institutes (see §2.5).

Institutional interdisciplinary focus is provided by the University Strategic Interdisciplinary Research Institutes SMMI and IfLS (REF5a §2.6). SMMI (led by **Teagle**, 46 SOES members; 36M/10F) projects UoS's distinctive maritime research pedigree and represents a key hub for academics across UoS and commercial and public sector marine and maritime organisations, including those local to Southampton, one of the UK's most important maritime cities. Significant outcomes include the establishment of a new research field in substrate controls on the life-time performance of marine high-voltage (HV) cables, which brings together SOES geoscientists with electrical and civil engineers from Faculty of Engineering (see ICS4).

The IfLS (22 SOES members; 16M/6F) supports interdisciplinary research across UoS within the full remit of the life sciences. **Ezard** currently leads the “Evolution” Research Theme that examines how living systems change over time and **Wiedenmann, Hauton, Lam** led the “Global Change: Systems & Cycles” Research Theme explicitly recognising the need for a multi-level (molecular through to Earth System) perspective in addressing complex challenges in the environmental biosciences.

SMMI and IfLS both support interdisciplinary research through cross-campus studentships and seed-funding schemes, meetings, workshops and conferences (e.g. the IfLS international 'Life in a High Carbon World' meeting held at NOCS in 2015). Other notable examples of interdisciplinary activities across UoS have included: (i) geochemists working with archaeologists and anthropologists to reveal the Neanderthal origins of cave art (**Milton**); (ii) marine biologists working with medical lipidomic mass-spectrometrists to understand the nutrient stress response of phytoplankton (**Mills, Moore**) and symbiotic coral algae (**D'Angelo, Wiedenmann**); (iii) ecophysiologicals, geophysicists, geochemists and lawyers working on the impacts of leakage from geological CO<sub>2</sub> storage (**Bull, James, Gernon, Hauton**); (iv) SOES biogeochemists working with NOC engineers and commercial companies to develop novel sensors for autonomous measurement of macronutrients, trace metals and primary productivity (**Bibby, Lohan, Moore, Hickman**); (v) microbiologists and geochemists collaborating with the mining industry on carbon sequestration via mineral carbonation (**James, Lam, Matter, Teagle**); (vi) joint projects between SOES staff and the Cancer Immunology Centre to improve shrimp aquaculture conditions (**Hauton**); and (vii) physical oceanographers working with researchers in Geography and Politics on the tele-connected risks in the Atlantic of the expanding “Great Sargassum Belt” (**Marsh, Skliris**).

### 1.7 Developing an open research environment

SOES is committed to opening up all stages of the academic workflow from data generation and analysis through to dissemination of outputs to diverse audiences.

Our staff take leading roles in generating new resources, e.g. through the UKOA programme ([https://www.bodc.ac.uk/projects/data\\_management/uk/ukoa/](https://www.bodc.ac.uk/projects/data_management/uk/ukoa/); 99 datasets); museum collections (**Fenberg**: iCollections of British Butterflies and Moths at the NHM and the Digitised British Odonata collection, total >190k specimens; **Ezard**: the micropaleontological Buckley Collection of planktonic foraminifera) and by submitting over 300 data sets to Pangea, BODC and elsewhere since 2014. A component of the British Oceanographic Data Centre (BODC) is also co-located at NOCS, facilitating innovation in data science.

SOES staff also facilitate the availability of open access data through international programmes such as GEOTRACES (**Lohan**, Scientific Steering and Standards and Intercalibration Committee member) and COMPADRE (**Ezard**, Core Committee Member). We are leading (**Haigh**) the creation and dissemination of information on historical flooding through ‘SurgeWatch’ (<https://www.surgewatch.org/>), in collaboration with NOC and BODC, alongside the Global Extreme Sea Level Analysis global tide gauge data (<https://www.gesla.org/>; see ICS2).

Through increasing publication of our analytical code and models and by striving to make these outputs more accessible to the general public, we promote transparency in our science, e.g. via a smartphone app of an Earth system model (<http://www.co2modeller.info/>; >2500 downloads; **Goodwin**) to better inform the public of the effect of carbon emission reduction on climate, and through other interactive web apps (e.g. <http://pyramids.cpc.ac.uk/>).



Open access publishing is undertaken in accordance with the UoS Open Access Policy, with the 'green' route utilising the UoS-developed 'EPrints' platform (REF5a §2.4). The percentage of SOES SCOPUS-listed research outputs published in open access has risen from <80% (2017/2018) to >86% (2019/2020), including >50% with gold OA. Multiple SOES staff members are also associate editors for open access publishers such as Nature Scientific Data (**Haigh**), Frontiers (**Haigh, Lam, Kier, Moore, Mills, Sims, Townend, Wiedenmann**), EGU Copernicus (**Marsh**), and Geochemical Perspective Letters (**Foster**).

### 1.8 Supporting a culture of research integrity

SOES is committed to high standards of research integrity and governance (REF5a §2.8). The culture of research integrity within SOES is embedded through the research groups, under the leadership of the group heads, alongside a staff mentoring and appraisal process which focuses on excellence, accountability, transparency and responsiveness. Training in research integrity is provided to PGR students through GSNOCS and the UoS Doctoral College (see §2.5). Ethics review is organised via the Ethics and Research Governance Online UoS system, with Robert Robinson (aquarium manager) a member of both the Faculty Ethics committee, and the University Animal Welfare and Ethical Review Body. All staff are required to complete an annual register of interests return in accordance with the *UoS Conflict of Interests Policy*.

## 2. People

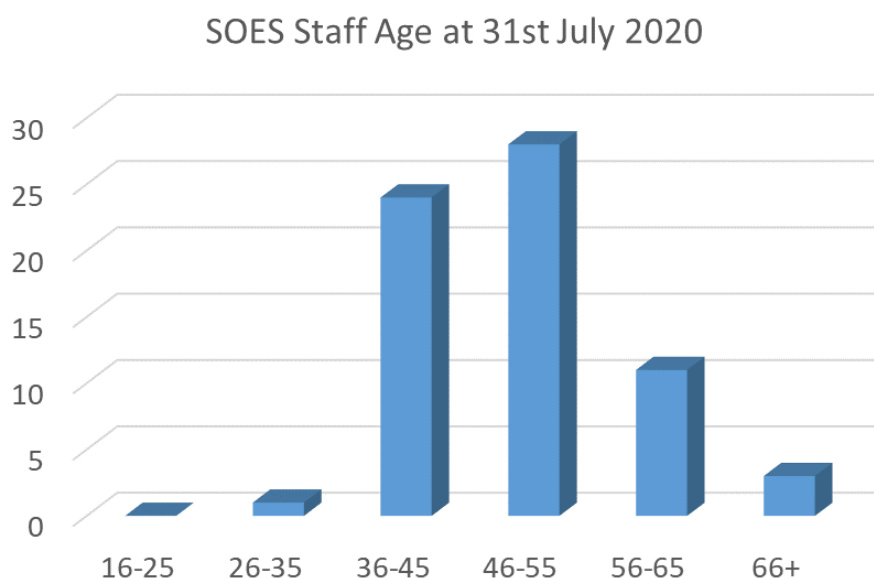
### 2.1 Staffing and recruitment strategies

The international quality of SOES activities stems from the combined excellence and diversity of our staff which facilitates the versatility and adaptability required to address emerging challenges in the Ocean and Earth system (see §1.4). Strategic areas for recruitment are identified by considering: (i) synergies between our research, education, enterprise and impact priorities; and (ii) the nature of existing facilities, potential areas of future infrastructure investment and the external funding landscape. Recruitment across all levels is characterised by a global search via adverts in leading journals, online and using social media platforms. Staff undertake active searches, through their collaborative networks and at national and international meetings and conferences, where possible, placing a particular focus on underrepresented gender and ethnic groups. Short-listing, interviews and decision-making are carried out by panels chaired by experienced staff, informed by open school-wide consultation. All staff undertake comprehensive and appropriate Equality Diversity & Inclusion (EDI) training.

Following significant expansion prior to 2014, we continue to pursue an overall strategy of consolidation and enabling as outlined in our REF2014 submission. Since the REF2014 census we have: (i) appointed 8 staff to permanent University positions (**Cundy, Ezard, Godbold, Gibbs, Goodwin, Hickman, Hain, Lohan**, 4M/4F) and recruited 4 Independent Research Fellows (IRFs; **Annett, Ward, Inglis, Coggon**, 2M/2F); (ii) recruited 3 apprentice technical staff, all of whom transitioned to open-ended contracts within SOES; and (iii) appointed Prof. Harry **Bryden** (FRS) as the inaugural Regius Professor in Ocean Science following the award of the Royal Warrant to SOES/UoS in 2016. In total 10 SOES staff from our 2014 submission have retired (10M) while 9 staff left (4M/5F), in most cases to take up positions overseas including the USA (**Beaulieu, Hain**, University of California Santa Cruz), France (**Sevellec**, Université de Bretagne Occidentale), Canada (**A.Bates**, Memorial University, **Weitemeyer**, now at OFG Inc.), Australia (**Zika**, now at University of New South Wales) and Germany (**Achterberg, Gledhill**, GEOMAR).

Appointments in priority areas identified in our REF2014 submission included a senior academic position in radiochemistry (**Cundy, M**) and new appointments (2F) in biogeochemistry (**Lohan, Hickman**). Priority areas in autonomous marine observing and coastal oceanography have been reinforced through new activities of current staff (coastal: **Dix, Haigh, Hickman, Lohan, Purdie, Solan, Thompson**; autonomy: **Dix, Lohan, Moore**), the latter in collaboration with staff across other UoS faculties (**Thornton**, Engineering and Physical Sciences) and NOC.

This REF period has seen many of our younger staff become established members of the School, and hence we currently have an age profile that is strongest in the mid-career stages (Figure 1). To complement this, recruitment over the coming period will continue to focus on early career researchers (ECRs).



*Figure 1. SOES Cat. A Staff by Age*

We remain a diverse department with 7% BAME and 27% of our staff being international. Improving staff gender balance at all levels has been a recruitment priority and female representation in SOES is now 27%, higher than at REF2014 (22%).

## 2.2 Staff recruitment, development and support

Researcher development is supported across UoS by the *Centre for Higher Education Practice* (CHEP; REF5a §3.5). Within SOES, all staff have a line manager and are encouraged to sign up to an independent mentoring programme. Research groups provide collegial support and advice to staff across all levels. Staff well-being is further supported through UoS-wide activities (REF5a §3.4), reinforced by the local SOES well-being champion (Moir MacLean). Staff induction is undertaken by the line-manager in co-ordination with research group heads. Researcher development is supported as follows:

### 2.2.1 Support for fixed-term ECRs (PDRFs and IRFs):

Career development of fixed-term researchers in SOES is aligned with UoS policy and practice (REF5a §3.5). In addition, SOES (together with NOC) has its own ECR network led by a member of faculty, an independent research fellow and a PhD student. Events to facilitate ECR development have included grant evaluation workshops, activities to guide independent research fellowship applications, and a residential workshop focused on working with industry. Exceptional contributions to collegiality, quality, internationalisation or sustainability are

recognised by the ECR Dean's Prizes; SOES staff have received 14 of these awards over the review period. All Post-Doctoral Research Fellows (PDRFs) are encouraged to request an independent mentor and consider the development of their own ideas through submission of grants as 'researcher-Co-Is' and/or IRF proposals.

Our 4 (2M/2F) Royal Society or NERC-funded independent research fellows (**Annett, Coggon, Inglis, Ward**) are represented on SOES committees and encouraged to contribute to teaching and co-supervision of PhD and masters students. SOES has a strong track record of bringing IRFs through to open-ended positions, and the importance of this route is well recognised by many of our senior research leaders who previously underwent this transition themselves (**Bibby, Foster, Hauton, Moore, Minshull, Naveira-Garabato, Rychert, Wiedenmann**).

#### *2.2.2 Support for Education, Research and Enterprise (ERE) 'academic' staff:*

New staff are supported in developing their research over an initial two-year probation period (one-year for senior appointments), and subsequently, through informal and formal mentoring and training and by reduced teaching and administrative loads in the first three-years. Research infrastructure requirements for new academic staff are supported through a start-up package (including PhD studentships), alongside full integration of new staff into the collegial culture of the School.

Research grant applicants are mentored by experienced staff, and proposals are internally reviewed prior to submission; the success rate for SOES NERC Discovery Science applications increased from 5% (2014-15) to 20% (2018-19). Periods of one semester study leave are encouraged every four years (during 2014-2020, 35 staff had sabbatical leave), and are enabled through re-allocation of teaching and administrative responsibilities.

A testament to the success of our approach to development and support is that during the REF period 35 ERE staff were promoted (24M/11F), including 16 to associate professor (10M/6F) and 14 to full professor (11M/3F).

#### *2.2.3 Support for Technical and Experimental (TAE) staff:*

TAE staff are vital for sustaining SOES excellence in research, enterprise and impact. UoS is a signatory of the *Technician Commitment* and SOES policies and cultures aim to recognise the 4 pillars of visibility, recognition, career development and sustainability. TAE staff are all embedded within research groups and line managed and mentored to ensure career progression opportunities.

### **2.3 Recognition and reward for research and impact**

Aligned with the UoS 'Reward and Recognition' strategy (REF5a §3.1), clear targets and expectations for achieving research with impact are agreed between staff and line-managers in appraisals. Contributions to research, enterprise and impact are thus key staff performance indicators allowing merit-based promotion. Staff making a strong contribution to enterprise activities can adopt the enterprise pathway within the ERE job family (**Milton**, Michael Grant, David Reading, **Warwick** (now balanced)). Exceptional contributions by both TAE and ERE staff across all areas are recognised within the annual Dean's and Vice Chancellor's awards, awardees over the current period including **Haigh** (Impact), TAE staff Neil Jenkinson (career service), and Aaron Billen and Matthew O'Shaughnessy (collegiality).

## 2.4 Procedures to promote interactions outside of academia

The SOES Stakeholder Advisory Board provides a key focus to develop links with non-academic sectors. SOES staff can also apply for sabbatical leave to develop new links or strengthen existing ones with industry, public or third sector bodies. For example, **Gernon** spent his 2014/15 sabbatical at the Chilworth Business Incubator at the University of Southampton Science Park (see “A sabbatical reboot” *Science* doi:10.1126/science.370.6517.738). SOES’s Impact Champion (**Gernon**) supports staff in applying for the University’s UKRI-funded Impact Acceleration Accounts, and other schemes, including the internal Public Engagement with Research Development Fund and a policy commission competition run by Public Policy|Southampton (REF5a §2.9). The FELS REF Impact Officer (Lisa Hanley), provides further support, including assistance in the production of ICSs (e.g. funds were awarded for the development of apps (ICS2), for public exhibitions (ICS3) and engagement with stakeholders (ICS5)).

Our Impact Officer and the University’s Marketing and Communications group support our staff in promoting their research outside academia via: school visits, web resources, open days and ‘Discover Oceanography’, participation in science and employment fairs, broader outreach events such as *Pint of Science*, and summer schools supported by Headstart and BG group to widen participation. Other notable activities with a strong element of public and societal engagement, beyond ICS1 and 3, include workshops and symposia (e.g. at the UN Global Platform for Disaster Risk Reduction, **Godbold**), and engagement with public audiences via radio (e.g. **Mills** featuring in the BBC’s “the Life Scientific”) and other media, in addition to public lectures, articles and podcasts (e.g. **Foster** on the BBC’s CrowdScience). SOES also has the largest Student Ambassadors Scheme in the UK placing >60 undergraduates into schools to support STEM teaching and provide role models.

## 2.5 Research students

Postgraduate student activities are co-ordinated through our world-renowned Graduate School of NOCS (GSNOCS), which currently comprises 200 doctoral researchers (89M/111F), representing a large, diverse, vibrant and international community of interdisciplinary researchers which spans our research portfolio. Around 90% of our staff, including 4 SOES ECRs and all 4 of our IRFs, have supervised PhD students over the REF period. The Southampton-based component of NOC is fully integrated within GSNOCS with NOC research staff engaged in supervision, training, recruitment, and progress-monitoring of graduate students. The two SOES-led NERC DTPs (SPITFIRE (2014-2019) and INSPIRE (2019-2024), <https://projects.noc.ac.uk/inspire/>) and the SOES-led NERC NEXUSS Centre for Doctoral Training (CDT; <https://www.southampton.ac.uk/nexuss>) play particularly important roles in enhancing research collaboration between UoS and external HEI and non-HEI research organisations nationally and globally (see §1.6 & 4.1; Figures 2 & 3). Our successful bid for an increase in studentships to the second phase of NERC DTPs provides an external measure of the success of GSNOCS. INSPIRE recruits a nominal 16 students per year (44 students with co-funding in cohorts 1&2).

### 2.5.1 Recruitment:

GSNOCS recruits ~40 PhD students per year, with a strong international membership (~40% from the EU and overseas), supported by a variety of: NERC DTPs, CASE, and tied awards, EPSRC grants, Leverhulme awards, BBSRC South Coast Biosciences DTP, University (e.g. SMMI, IfLS, and Vice Chancellor’s awards) and NOC funds, and a range of European and

international scholarships, as well as direct industry support. PhD projects are developed by supervisors and peer-reviewed by colleagues before being widely advertised on the GSNOCS website, FindAPhD.com and elsewhere. Our philosophy is to attract the best students possible and facilitate the most appropriate project for them.

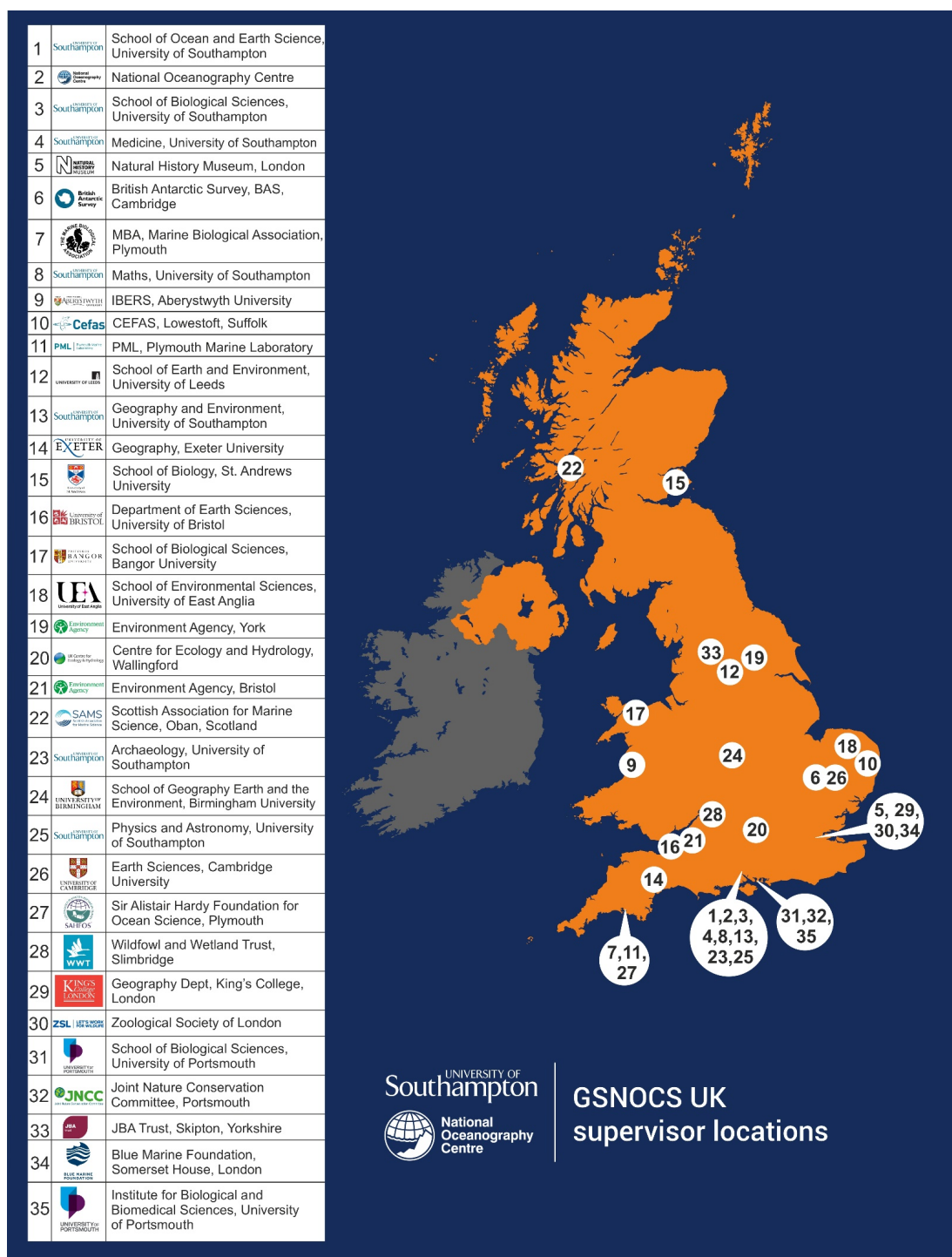


Figure 2. Locations of UK (co-)supervisors of GSNOCS PhD students. All projects require a UoS supervisor but involvement in our grad school spans the UK.

Students selected for interview visit NOCS for a full day that includes an independently chaired panel interview. Applicants are assessed according to their academic record, fit to topic, personal statement and references, as well as interview performance. This rigorous but fair process is undertaken by EDI trained interviewers and results in a diverse (see §2.6, Figure 5)



post-graduate community (averaging 49%M/51%F), recruited on the basis of candidate uniform excellence, with availability of co-funding and external sponsorship as secondary criteria. GSNOCS ensures similar recruitment processes for DTPs and other funding sources and has a standard of entry. Our Masters in Research cohort comprises ~10 students per year, >30% of which immediately progress onto a PhD.

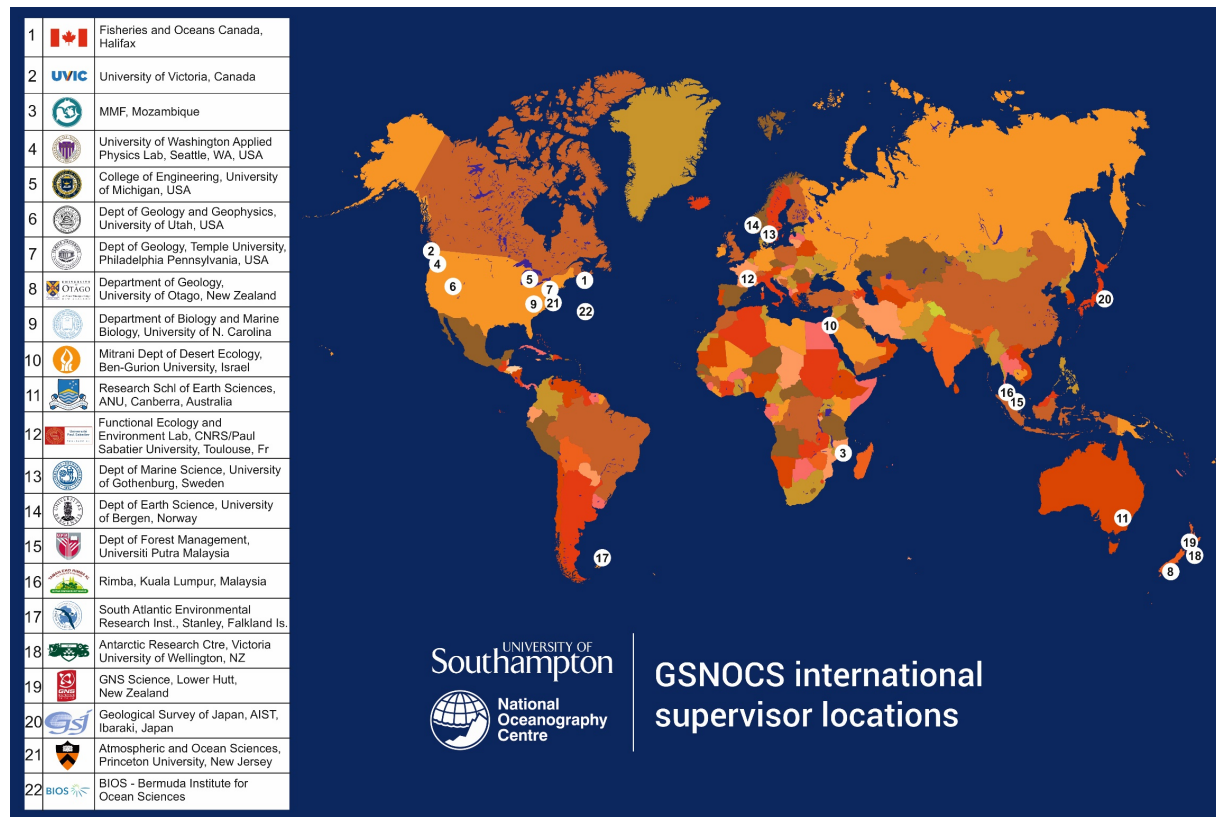


Figure 3. International locations of co-supervisors for GSNOCS PhD Students illustrating the global reach of our graduate school.

### 2.5.2 Training and support:

All PhD students receive UKRI level stipends (or higher) and have equivalent supervisory provision and, where appropriate, identical training opportunities (aligned with UoS practices, REF5a §3.7). Some programme-specific activities are associated with individual DTPs/CDTs (e.g. training on autonomous platforms within the NERC NEXUSS CDT). All students engage in a diversity of subject-specific training as well as generic skills training, including that facilitated by the UoS Doctoral College and CHEP (REF5a §3.7).

All PhD students are expected to attend international meetings, and encouraged to participate in international exchanges and placements with leading national and international research (e.g. BAS, Woods Hole Oceanographic Institution (WHOI), Scripps Institution of Oceanography), industrial (e.g. Spire Global, OptaSense, SRK Consulting) and governmental (e.g. Natural England, Department for International Development; Foreign and Commonwealth Office) organisations. Since 2014, >85 students participated in such placements. All GSNOCS students are also encouraged to take advantage of our close engagement with international programmes (e.g. IODP, GEOTRACES, GCOS/GOOS) even if these are not directly related to their research project; nearly all PhD students undertake (inter)national fieldwork, including cruise participation, during their studies.

### 2.5.3 Monitoring and Outcomes:

Students have an Advisory Panel that includes their supervisory team and an independent Chair. Progress is reviewed at least annually with written evidence provided to the Head of GSNOCS (**Palmer**) in a format designed by recent PhD students. Confirmation of PhD registration occurs after 18-21 months and involves a departmental talk, a written report and a viva chaired by the Advisory Panel Chair and an independent assessor.

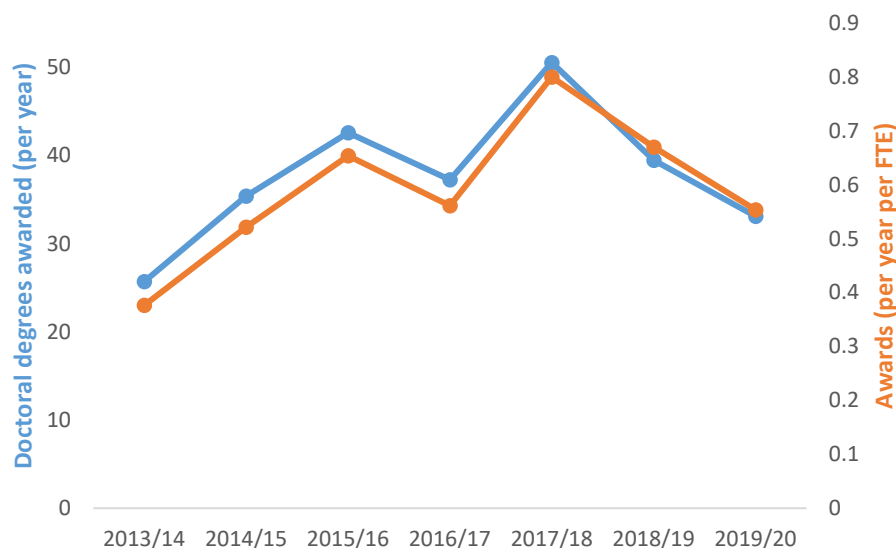


Figure 4. Doctoral completions by year and per staff FTE that year over the current REF period.

This QA system is key to GSNOCS delivery of highly successful outcomes, evidenced by an average time to submission of 3.88 years. Sustained high intake rates and high completion rates combined to drive a substantial increase in awards over the early REF period (Figure 4) with one completion per supervising staff FTE every ~1.5 years. Over 80% of GSNOCS graduates are employed in highly-skilled first destination jobs (48% academic, 18% in Industry, 14% in Government and 20% in other forms of employment; GSNOCS survey, data 2014-2020).

## 2.6 Equality, Diversity & Inclusion

EDI is a key component of the SOES strategy, facilitating excellence, capacity, sustainability and agility. Development of EDI strategy and policies, alongside improving practice and monitoring outcomes, is overseen by the SOES EDI Committee (chair **Trueman**) and ensured through an action plan informed by biennial SOES well-being surveys and regular topic-specific focus groups. The SOES EDI strategy recognises all protected characteristics and in particular ongoing national EDI challenges related to gender (Figure 5) and ethnicity representation in STEM disciplines. SOES staff play a key role in the institutional commitment to EDI detailed in REF5a §3.8, e.g. **Ezard** and **Godbold** are members of the Institutional Athena Swan Self-Assessment Team. Externally to UoS, we promote EDI by providing the Chair of Athena Swan Panels for Earth and Environment for the Equality Challenge Unit (**Bull**). During the last staff survey >80% of staff agreed that SOES is 'a great place to work'.

SOES policies and working practices for staff and student recruitment and development and progression are subject to review by the SOES EDI Committee. All staff are required to undertake EDI training, including unconscious bias training (>90% completion). A culture of EDI is reinforced by ensuring the broadest possible representation of all protected characteristics on all School committees and is embedded within SOES through inclusive open calls for promotion

and reward applications, with expressions of interest solicited from appropriate levels across SOES for all senior roles.

We support flexible working (granting between 3-8 requests per year) and all departmental meetings are scheduled within core hours (10:00-16:00), rotating across different time and day slots, to facilitate participation of part-time staff. We developed guidance for the Faculty regarding: i) support for academic and research staff during family leave, and ii) return to work following long-term leave. Staff can additionally apply for career breaks of 1-3 years to undertake extended caring responsibilities, periods overseas with relatives, or to work toward further qualifications. In our most recent survey, more than 80% of staff agreed that SOES '*provides them with adequate provision to work flexibly and support caring responsibilities*'.

Complementary to the Athena Swan Silver award held by UoS (REF5a), in May 2018, SOES achieved renewal of a departmental Bronze award for the development and implementation of equality and diversity policies to progress cultural change. Our equal opportunities, flexibility and benefits strategies are reflected in statements used in all job adverts. Since 2015 we have increased the proportion of female applicants across all advertised posts. Over the REF period 75 Postdoctoral research assistants (level 4), and 4 Independent Research Fellows and 8 Staff (levels 5 & 6) were recruited of which 44% and 50% are female, respectively. To support progression, we have implemented a policy that ensures all ERE staff are reviewed for promotion at least every three years. We have introduced annual appraisal and promotion seminars for all staff to inform on process and responsibilities and highlight expectations. Feedback on promotion applications is provided by an informal promotions panel (chair **James**).

As a measure of success of these efforts, since 2013/14 we have had 63 applications for promotion, of which 27% were female, and applications for promotion from female members of staff were successful on average 81% of the time (vs. 76% from male staff). Female representation has increased from 3 (14%F) to 5 (23%F) for associate professors and from 2 (7%F) to 4 (13%F) for professors from 2013 to 2020 (Figure 5), this alongside a female Deputy Head of School Research (**James**) and Dean of FELS (**Mills**), with 27% female representation across the whole cohort of REF2021 submitted staff (compared to 22% for REF2014). Seven female members of research and academic staff have benefited from the Continuity to Career scheme (established by SOES in 2013 and now rolled out faculty-wide), a scheme that offers research support for those returning following extended periods of family leave (e.g. maternity or adoption leave).

We will continue to develop and advance our EDI action plan over the coming REF period, including submission of a departmental Athena SWAN Silver application, close monitoring of and continued efforts to retain and promote female staff (i.e. 'plugging leaks' in the 'pipeline'; Figure 5) and a renewed focus on enhancing processes to encourage increased representation of lower socio-economic groups and more ethnic diversity across our staff and student profiles.

Development of the current REF submission was the responsibility of the SOES REF committee (**Moore/Foster, James, Gernon, Roberts, Rohling, Bull**). Consultation across the whole school was ensured through a dedicated REF away-day focused on the development of ICSs, alongside comprehensive review of the environment statement, facilitated through group heads and the chair of the EDI Committee (**Godbold/Trueman**), complemented by individual staff interviews. Following the UoS Code of Practice (REF5a §3.9), outputs were first self-selected by all balanced and independent research-led staff. These were then assessed by a diverse independent panel on the basis of originality, significance and rigour, followed by moderation by the REF committee. Analysis revealed no evidence of gender bias, with the gender balance of

our REF2 submission very similar to that of our returned staff (71%M 29%F in outputs vs. 73%M and 27%F for Staff).

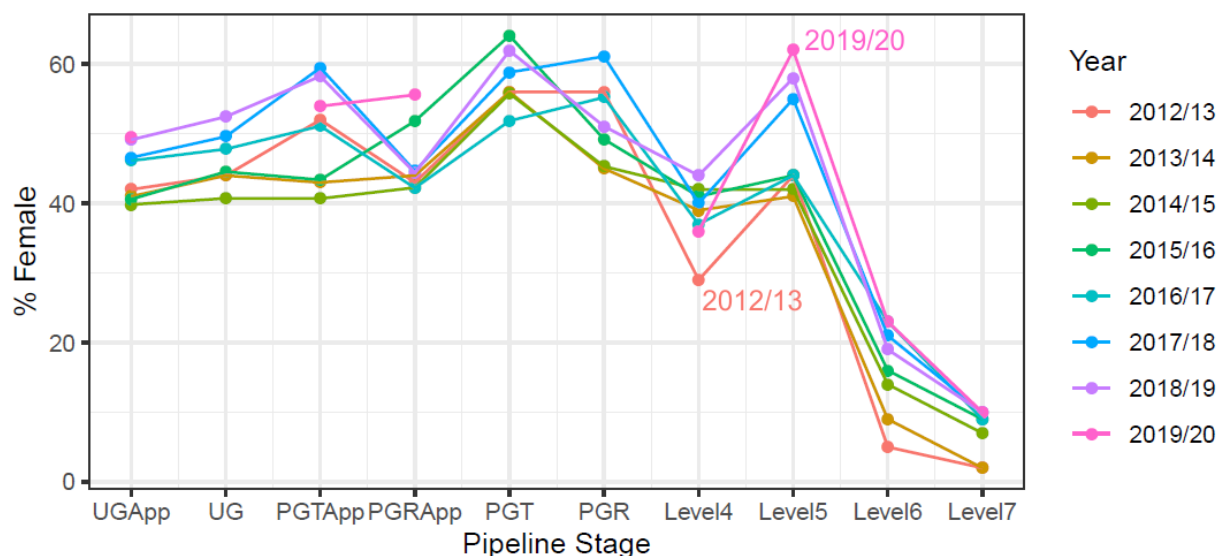


Figure 5. Gender breakdown of students and staff at all levels, illustrating hiring and career advancement-led growth in female representation at levels 5-7.

### 3. Income, infrastructure and facilities

#### 3.1 Research funding portfolio and plans

Our total research income over the REF period was £39.99M, an average of £5.71M/year, compared with £4.93M/year in REF 2014, an increase of 16%. Average annual grant income was £95k/FTE, and £123k/FTE including research income-in-kind. Research income (Figure 6) from UKRI sources was £26.1M, with other major funders the European Commission (£7.9M) and UK-based charities (e.g. Leverhulme Trust, British Ecological Society, Marine Stewardship Council, English Heritage, Wellcome Trust; £2.2M). Research funding from UK industry amounted to £1.8M, including £400k from the Arcadia Fund for the Deep Sea Ocean Stewardship Initiative.

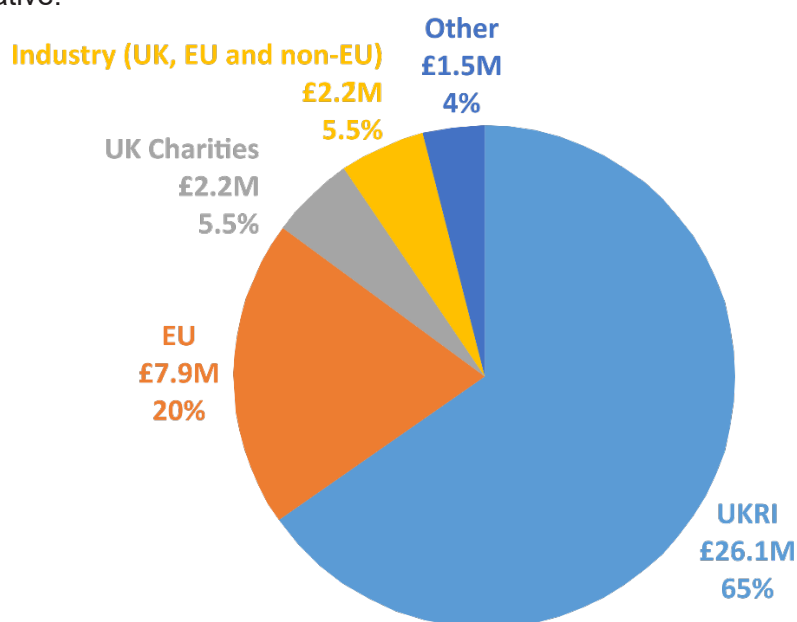


Figure 6. Research income over the current REF period. UKRI, Charities and EU funding dominates current income, demonstrating potential for future diversification.

Major individual awards (>£0.5M to UoS) included SOES leadership of the NERC-funded projects PISTON (£2M), MerMEED (£0.9M), CHIMNEY (£0.6M), STAFES-APP (£0.5M), SONIC (£0.5M), and the European Commission (EC) project SO-CHIC (£0.6M), major partnership in the EC project STEMM-CCS (£1.8M), and two European Development Agency grants (£0.7M total). European Research Council grants were secured by **Rychert** (StG, £1.2M), **Foster** (AdG, £3.2M; awarded April 2020), **Sims** (AdG, £2.3M; awarded April 2020), **Brownlee** (AdG, £2.4M), and **Frajka-Williams** (StG, £1.8M).

Inclusivity in research activities across SOES is reflected by: (i) 78% of individuals having secured external funding over the REF period; (ii) female academic staff (27% of permanent staff) being PI on 23% of overall research income (£9.3 M), including 2 of the top 6 highest individual research incomes (**Rychert, James**); (iii) significant research income (£1.7M) secured by 2 individuals who took parental or carer leave over the census period; (iv) ECRs being responsible for 5% of income (£1.8M), primarily in the form of 4 IRFs (**Annett** (F), **Coggon** (F), **Inglis** (M), **Ward** (M)).

Enterprise activities within SOES are focused in two dedicated enterprise units supported by strategic investment of SOES staff time and facilities: the GAU-Radioanalytical (formerly known as Geosciences Advisory Unit) and Coastal and Offshore Archaeological Research Services (COARS). GAU-Radioanalytical provides radioanalytical consultancy and services to the nuclear industry, environmental sector, academia and local government and in 2018-19 had a turnover of £580k. GAU-Radioanalytical has supported significant nuclear decommissioning programmes including Magnox (across 12 nuclear licensed sites) and G E Healthcare (at both its Cardiff and Amersham sites). GAU-Radioanalytical is one of only six laboratories providing radioactive waste characterisation services within the Low-Level Waste Repository waste characterisation framework. In 2019, GAU-Radioanalytical (**Warwick, Cundy**) was awarded £1.2M by EPSRC to establish NNUF-EXACT, a world-leading radiochemistry facility enabling research and training in accelerated nuclear characterisation and remediation technologies. This, along with membership of the Southwest Nuclear Hub, provides a further key interface between academia, government and the nuclear industry. COARS, founded in August 2013 with a turnover of £75k per annum, has provided marine archaeological consent support for various offshore infrastructure projects including major UK windfarms, high voltage interconnectors and fibre optic telecommunication cables. Their 3D Chirp system also undertakes commercial work in collaboration with SAND Geophysics Ltd (a local marine survey company set-up by UoS alumni) on a range of riverine, coastal and offshore projects (e.g. major work on the Thames Tideway Tunnel) with £120k revenue in the last 2.5 years. COARS also provides a Continuing Professional Development training course in marine geoarchaeological assessment for English Heritage and the offshore energy sector.

We will support our strategic research objectives (see §1.4) by sustaining our major UKRI income and growing and diversifying our funding portfolio by not only building on recent successes in terms of increasing the range of funding councils applied to (e.g. >£1.5M BBSRC, **Hauton, Bibby, Moore** and >£2.5M total EPSRC, **Cundy, Warwick, Beaulieu and Teagle**) but also through industrial and charitable streams, with leadership provided by the newly-established Director of Enterprise (**Dix**). The latter will include targeting opportunities and links provided by KTN, Innovate UK and the series of Royal Society Entrepreneurs in Residence associated with UoS. Successful grant capture will continue to build on a foundation of research excellence developed through our staffing strategy (see §2.1, 2.2), alongside the effective mentoring of staff and associated proactive collegial support for development of proposals including actively



seeking and mentoring applications for personal fellowships by ECRs. We will continue to input ideas to NERC on areas for targeted strategic funding aligned with our objectives (see §1.4), while also horizon-scanning for upcoming challenges aligned to our expertise and facility capabilities (see §3.3). By leading and participating in applications to such strategic funding calls, we will build on our extensive network of national and international collaborators (see §4.1) and our overall versatility and adaptability strategy (see §1.4, 2.1).

### 3.2 Organisational infrastructure supporting research and impact

The National Oceanography Centre Southampton is a purpose-built world-class research facility. It is well-maintained and continually upgraded to ensure compliance with current regulations and guidelines, including accessibility. Examples over the review period include installation of accessible workspaces, fitting induction loops in lecture theatres, installing lifts with fully retractable doors, and applying contrasting colours in corridors to facilitate accessibility for the visually-impaired. A well-being room to support staff requiring rest breaks and expressing mothers was also established. A NOCS-wide Environment Advisory Group (including GSNOCS representation) seeks to minimise the environmental footprint of the building with a range of activities from encouraging sustainable transport and installing solar-powered showers to the introduction of sustainably-sourced food in the canteen. NOCS has achieved ISO14001 certification for its environmental management system and ISO45001 certification for its occupational health and safety management system. Continuous improvement in all areas is part of the certification of ISO14001.

Each SOES research group operates and/or utilises state-of-the-art facilities run by core experimental officers who are responsible for facility management and development. SOES has benefitted from University investment in developing the UK's largest towing tank (£25M partly from external sources) and its high-performance computing infrastructure (IRIDIS; over £50M since 2014). Significant SOES investment into facilities since 2014 includes: (i) an Environmental Sequencing Facility that provides a range of next-generation sequencing and analysis services (£1.7M); (ii) an Organic Geochemistry laboratory comprising several GC- and HPLC-mass spectrometers (£0.5M); (iii) a state-of-the-art Palaeomagnetism Facility (£0.5M); (iv) laboratories for carbonate analysis and water-rock-carbon dioxide reaction experiments (£1.1M); and (v) an inductively coupled plasma time of flight mass spectrometer (icpTOF, one of the first in a UK HEI) and a triple-Quad ICPMS (£0.5M) for geochemical analysis. These investments were funded by competitively awarded grants, central UoS funds and by an equity sale from a SOES spin-out (OHM; £0.7M). All facilities are supported within both general and specialised laboratory spaces, the latter including an extensive suite of clean laboratories for both chemical and microbiological work.

### 3.3 Operational and scholarly infrastructure, including specialist facilities

Facilities operated centrally by SOES include: our coastal and shelf research vessel the *RV Callista* (20m catamaran), which is supported by 1.6 FTE TAE staff (3M); and our sample preparation/thin-sectioning laboratory (2 FTE TAE staff, 2M). The National Oceanographic Library (NOL), hosted at NOCS, is run by UoS in collaboration with NOC as a resource for staff and students across SOES and UoS, the wider UK marine science community and public (by appointment). Other facilities are operated by individual research groups but are available to all staff as well as external users, representing a substantial income stream (e.g. the Geochemistry Facility receives ~£80k pa, research vessel ~£20k pa and the Environmental Genomics Sequencing Facility ~£10k pa).

Key infrastructure including specialist facilities by research group include:

**GC:** Operates a state-of-the-art clean lab and mass spectrometry laboratory, equipped with two multi-collector Inductively Coupled Plasma Mass Spectrometers (ICP-MS), three ICP-MS (including the recently purchased triple-Quad), a Thermal Ionisation MS and a new icpTOF, collectively representing one of the most comprehensively equipped inorganic geochemistry facilities in a UK HEI. We recently established an organic geochemistry laboratory with GC- and HPLC-MS and a GC-isotope ratio MS (£0.5M). Additionally, a low-temperature water-rock-carbon dioxide experimental laboratory was developed hosting a stable inorganic and organic carbon analyser, coupled to a Cavity Ring-down Spectroscopy analyser, alkalinity titrator and pH-stat instruments.

**G&G:** Maintains the best equipped marine geophysical pool within a UK HEI, having a complete suite of conventional and bespoke equipment (e.g. a shallow and deep water swath; 3D Chirp; high-resolution multi-channel streamers; and deep-towed electromagnetic source and receivers), and equipment to perform seafloor Controlled Source ElectroMagnetic surveys alongside the Ocean Bottom Instrumentation Consortium (OBIC) co-run with Durham University. We also support four well-instrumented sediment flumes, larger scale flume infrastructure on the Boldrewood campus and have 2D and 3D sediment tanks which have been used for prototype HV cable experiments. We have a well-equipped sedimentology laboratory for standard sediment analysis including a range of field equipment (e.g. benthic landers, Conductivity Temperature Depth (CTD) probes, wave and tide pressure transducers, shallow water sonars). For research and teaching purposes we have licences worth ~£31M commercially for a range of top-end industry standard software: Petrel, 2D and 3D Promax, Caris, SonarWiz and CODA Octopus.

**MB:** Operates a macronutrient, total organic carbon and nitrogen and carbonate chemistry facility using standard instrumentation (e.g. VINDTA-3C) including recent investment in: a new sea-going auto-analyser (£45K), chemostat systems, imaging flow-cytometry and a range of state-of-the-art biophysics instrumentation (including novel autonomous *in-situ* systems developed as a collaborative industry project via the NERC Marine Autonomous Systems project STAFES-APP; £0.9M). Custom-built containerised laboratories are used for large scale experimental manipulation at sea. SOES operates the shared (UoS/NOC) state-of-the-art environmental sequencing facility, including a grade 2 molecular biological clean room, an Illumina MiSeq sequencer, and high-performance computing for bioinformatics.

**MB&E:** Operates two unique state-of-the-art mesocosm facilities: the Biodiversity and Ecosystem Futures Facility and the Coral Reef Laboratory aquarium facility. We also operate a multi-use research aquarium with a variety of tanks for keeping and handling live specimens for research, teaching and public outreach, host a hyperbaric experimental facility capable of maintaining *in vivo* experiments at high (full ocean depth) pressure, and have a new Acoustic, Sound and Vibration Ecology Facility (£240K, US Office of Naval Research) to study the impact of anthropogenic sound fields on coastal environments and ecosystems. Additionally, we have a biomineral/sclerochronology lab equipped for the imaging and micron-scale subsampling of hard tissues for chemical analysis.

**P&P:** Has invested >£1.3M to upgrade instrumentation for high-precision and high-sensitivity stable isotope ratio mass spectrometry and elemental analysis in a range of substrates (from oxygen and carbon isotopes in foraminifera to nitrogen isotopes in biological samples),

elemental analysis via Energy Dispersive X-ray analysis scanning electron microscopy, and palaeo- and environmental-magnetism with a new cryogenic magnetometer.

*PO*: Maintains a small suite of standard oceanographic equipment for deployment on the *RV Callista*, including two CTD systems, Acoustic Doppler current profilers and a towed undulating CTD system purchased in 2015 (£32k), and six pressure and temperature sensors. Open ocean observational work within *PO* is supported by the use of the NERC National Marine Equipment Pool (NMEP), which is based at the NOC. Past specialist equipment purchases within SOES-led NERC-funded science (e.g. microstructure profilers) are passed to the NMEP to facilitate wider community use. Modellers within the group are supported through access to a range of workstations, racks and high-memory machines alongside an on-site Mobilis 1152 core HPC and the UKRI Advanced Research Computing High End Resource (ARCHER).

### 3.4 Collaborative use of research infrastructure

Many of our research facilities have been and continue to be co-developed with NOC (e.g. the environmental sequencing facility and laboratories and instrumentation in the geochemistry facility). The OBIC, co-run by UoS and Durham University, provides the academic and commercial communities with access to instrumentation to image the sub-surface. The rest of our state-of-the-art marine geophysics equipment pool is also available for commercial hire. We make extensive use of key world-class UK facilities. Across all staff levels (i.e. Cat A. and PDRAs), SOES researchers have collectively spent >1500 days at sea on the NERC National Marine Facilities (NMF) ships operated out of both NOC (RRS *James Cook* and RRS *Discovery*) and BAS (RRS *James Clark Ross*), alongside making extensive use of the associated NMF equipment within the NMEP. We have made regular use of other national facilities including Diamond Light Source, ARCHER HPC facility, ion micro-probe facility and National Environmental Isotope Facility. We make use of many international infrastructure facilities including synchrotrons (Swiss Light Source), the ocean drilling activities co-ordinated by the Integrated Ocean Drilling Programme (see §4.1), and data from multiple components of the Global Ocean Observing System (GOOS) including the global ARGO float array and satellite remote sensing from both NASA and ESA platforms.

### 3.5 Benefits-in-kind

Halliburton has donated significant (~£31M) software for advancing our research in areas as diverse as rift fault activity at constructive plate margins to high resolution imaging of the subsurface to optimise the construction of offshore renewables. Research income in-kind equivalent to £11.6M is detailed in REF4c and is dominated by our leadership of NERC ship time activities.

## 4. Collaboration and contribution to the research base, economy and society

### 4.1 Research collaborations

We collaborate widely with HEI and non-HEI organisations across the UK, Europe and internationally. 23% of our total £40M research income was awarded from non-UK sources (including EU), while over 74% of our extensive portfolio of publications were co-authored with international collaborators and over 20 international institutions are associated with our PGR supervision and training via GSNOCS (Figure 3).

We are lead players in the IODP, arguably the largest, most enduring and successful long-term international collaboration in the environmental sciences: **Teagle** chairs the NERC-UK-IODP Programme Advisory Group and sits on the Executive Board that oversees the UK's subscription

to the international program; **McNeill** is Co-Chair of the international IODP Science Evaluation Panel; **Bohaty** is member of JOIDES Resolution Facility Board (previously **Wilson**). **Teagle** and **Coggon** oversaw the evaluation and successful renewal of UK membership of Scientific Ocean Drilling, representing one of NERC's largest long-term commitments (~£35M for ten years from 2019). **Coggon** is co-editor of the 2050 Science Framework strategy "Exploring Earth Through Scientific Ocean Drilling", for which she received a \$50k award from ECORD. **Coggon**, **Bohaty** and **Teagle** will be Co-Chief scientists on up-coming Expeditions 390, 392 and 393 which will include a number of Southampton-based PhD students and ECRs.

Other key contributions to major international programmes, include: €16M STEMM-CCS project (**James, Bull, Minshull**), €15M Blue Mining Project (**Minshull**), €12M EU MIDAS project (**Hauton, James**), €10M EU Initial Training Network project IsoNOSE (**James** (workpackage lead)) and £10M OMAN Drilling project (**Matter** (project director), **Teagle**) which involves 166 scientists representing 30 countries across five continents. We also make significant contributions to a number of joint NERC-NSF programmes including: BLT-Recipes and DynOPO projects (**Naviera-Garabato**, PI) and UK-US RAPID array through the NERC Atlantic Biogeochemical (ABC) fluxes project (**Moore, N.Bates**). We have made major contributions to the international GEOTRACES programme (**Lohan, Annett, N.Bates**). International GCRF collaborative projects included: Building resilience along the Colombian Caribbean coast (**Solan**) and SARTRAC (**Marsh**). A number of projects were also undertaken with >20 leading UK universities and research institutes, including the NERC strategic grants CHIMNEY (**Bull** (lead), **Matter, James, Minshull, Henstock**) and GGREW (**James, Lam, Teagle, Matter**) and NERC large grants PISTON (**Ezard**, lead), SWEET (**Foster, Inglis**), COMICS (**Lam, Moore**), DeCAdeS (**Naveira Garabato**) and RiftVolc (**Keir**).

We regularly host national and international visitors; these included 3 visiting UoS Diamond Jubilee Fellows (*Ben Van Mooy*, WHOI, USA 2013-2016; *Peter Keleman*, University of Columbia USA, 2013-2016; *Matt England*, University of New South Wales (UNSW), Australia, 2016-2019) and a UoS Global Fellow (*Jeffrey Alt*, University of Michigan, USA, 2019-present). The 5 formal seminar series run across SOES/NOCS play host to >100 research talks each year, with the flagship 'Friday Seminar Series' comprising >75 talks in the REF period (54%M/46%F), with 25% from international external speakers. SOES staff have also held a variety of visiting research/fellowship positions at institutions including: University of Sydney (**Bibby**); UNSW (**Marsh**); University of Florence (**Keir**); Hohai University, Nanjing Hydraulic Research Institute and State Key Laboratory of Estuarine and Coastal Research Shanghai (**Townend**); University of Western Australia and Vrije University Amsterdam (**Haigh**).

#### 4.2 Interactions with Research Users

Engagement with end-users is driven at both an individual level and through institutional support, guided strategically via the Stakeholder Advisory Board. Specific examples of end-user engagement are highlighted above (see §1.5) and include our ICSs. Southampton also hosts the NERC IODP Knowledge Exchange Co-ordinator (Jude Coggon) to better project the activities and impacts of IODP both within the environmental and the wider science communities, in industry, government and among policymakers. The success of these IODP-focused activities is reflected in the disproportionately high success rate of UK-led IODP proposals, and the diversity of UK engagement with IODP in terms of institution, gender, subject area and career stage.



### 4.3 Wider contributions to economy and society

Impact outside of academia is highlighted in our ICSs as well as broader activities. Examples of advice to policy-makers include: chapter lead (**Drijfhout**) and contributing authorship (**Foster**) IPCC AR6; development of DEFRA policy briefing on UK Shelf Seas (**Solan, James**); membership of DEFRA Science Advisory Council sub-committee on Ocean Acidification (**James**); provision of written and oral evidence to parliamentary select committees on subjects ranging from deep-sea environments (see ICS1), Ocean Acidification (**N.Bates**) and sustainable seas (**Mills**). We built capacity and provided advice on sustainable aquaculture and strategies for poverty alleviation in India and Bangladesh through the £2.1M Newton Bhabha consortium (UK BBSRC, ESRC, DBT India, DFID India) (**Hauton**), EU and NERC funded research on deep-sea mineral resources (£1M) informed the development of a regulatory framework for mineral exploitation on the high seas by the International Seabed Authority (**Hauton, Copley, James**). Work on the development of novel geochemical methods for fish traceability has also received funding from the Marine Stewardship Council (**Trueman**).

Beyond the contributions to the commercial sector detailed in ICSs 3, 4 and 5, we have undertaken commercial sensor development (**Moore**, Chelsea Technologies UK) and provided advice to geothermal exploration companies in Africa (e.g. Reykjavik Geothermal; **Keir**).

### 4.4 Community and public engagement

Public and community engagement is central to much of the work done in SOES, as detailed extensively in ICS1 and ICS3. Beyond these activities our Discover Oceanography programme gives school children and members of the public a unique, hands-on opportunity to experience marine science by taking part in experiments and collecting samples and data aboard *RV Callista*. Since 2014, >2500 individuals have participated including >15 different school groups a year from Hampshire and the wider south of England. SOES also contributed successful exhibits to the Southampton International Boat Show in 2015 and 2018. We developed two new 5-year exhibits at the Winchester Science Centre (WSC), one of which is their largest to date (**Godbold, Solan, Foster, Goodwin**). Since opening in Jan 2020, these exhibits have attracted >45k visitors, despite access to WSC being restricted due to COVID-19. SOES staff are also actively involved in the Southampton Science and Engineering Festival that attracts 8000+ people to engage in our research. Additionally, multiple SOES staff have contributed mainstream media interviews (e.g. **Bibby, Cundy, Wilson, Foster**), including an episode of the BBC 'Life Scientific' that has a potential audience of 10.7 million (**Mills**).

### 4.5 Contributions to sustainability of discipline

Since 2014, 20 SOES staff and >50 PG students and Post-docs have participated in UK or international research cruises, including 9 staff members that were principal scientists on research cruises using all of NERC's research vessels and other international vessels. Fourteen SOES scientists have sailed on IODP expeditions since 2014, 5 as Co-Chief scientists along with 5 early career researchers and PhD students. This level of IODP leadership and involvement is the highest of any UK HEI.

We provided members for 4 Scientific Committee on Ocean Research (SCOR) Working Groups on multiple topics including iron biogeochemistry (WG139, **Lohan**, WG151 **Moore**), microbial impacts of ocean deoxygenation (WG144, **Lam**) and fluorescence-based productivity measurements (WG156, **Hickman, Moore**) and a number of international model intercomparison projects, including RCMIP (**Goodwin**), DeepMIP (**Inglis, Foster**) and FeMIP



(**Moore**). Other working group activity included the International Ocean-Colour Coordinating Group "Role of Ocean Colour in Biogeochemical, Ecosystem and Climate Modelling" (**Hickman**); Transparent Ocean Group workshop for the UN Decade of the Oceans (**Marsh**); International Geosphere-Biosphere Programme Past Global Changes (PAGES) Varves (**Kemp**) and PlioVAR Working Groups (**Foster**); British Ecological Society Strategic Plan Working Group (**Ezard**); Scientific Committee of ecoSERVICES, (Future Earth; **Solan**); Steering Group of NASA/CNES Surface Water and Ocean Topography Adopt-A-Crossover Consortium (**Naveira-Garabato**); Royal Society Working Group on Foresight Future of the Sea (**Hauton**). Since 2014 we had 15 members on the NERC Peer Review College and provided >10 members for NERC grant moderating panels and fellowship interview panels. We also hosted and convened the Early Career IODP workshop in 2018 (**Teagle, Coggon, McNeill, Wilson**).

#### 4.6 International Academic Leadership

In addition to the leadership we provide to IODP (see §4.1), SOES staff have been members of multiple international institute advisory boards including: the Alfred Wegener Institute (**Tyrrell**); GEOMAR (**Minshull**); GFZ Helmholtz Zentrum Potsdam (**James**); marine science University of Bergen (**Minshull**), the University of Namibia Faculty of Engineering advisory board (**Palmer**); Institute Evaluation Panel of Royal Netherlands Institute for Sea Research (**Sims**); International Scientific Council of the South Ural State University (**Cundy**); and the review board of Bjerknes Climate Centre in Bergen (**N.Bates**).

We routinely provide reviewing and/or panel duties for international funding agencies, including: Norwegian Research Panel review panel Chair (**Naveira-Garabato**); Schmidt Ocean Institute Panel Member (**Mills**); Expert Evaluator of European Commission H2020 call LC-CLA-02-2019 (**James**); Canada First Research Excellence Fund panel member for Environment and Agriculture (**Mills**); Polish Roadmap for Research Infrastructures (**Bull**).

Other international roles included: Geohazards committee International Geoscience Programme (International Union of Geological Sciences and UNESCO) (**Cundy**); Advisory Board member, EU Horizon 2020 RETHINK project (**Copley**); 'Food from the Oceans' International Expert Network, Science Advice for Policy by European Academies (**Sims**). Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services Regional assessment for Europe and Central Asia lead author (**Solan**). Vice President (Europe) International board of the Society for Environmental Geochemistry and Health (**Cundy**). UK representative Antarctic Science Drilling (Andrill) Science Committee (**Bohaty**), UN International Oceanographic Congresses-SCOR on marine ecosystem time-series (**N.Bates**); Co-chair of Standards and Intercalibration Committee and Scientific Steering Committee member for GEOTRACES (**Lohan**); UN International Seabed Authority Council Meeting (**Hauton**).

#### 4.7 National Academic Leadership

SOES staff make major individual and collective contributions to the governance and operational activities of NERC, UKRI and the wider UK research community across multiple levels. The most significant of these include: Fellow of the Royal Society (**Bryden, Shepherd**); Trustee and Chair of Research and Enterprise Committee for Scottish Association for Marine Science (**Brownlee**); NERC Main Panel A Chair (**Bull**); British Ecological Society Honorary Treasurer (**Ezard**); National Environment Isotope Facility Strategy Group Member (**Foster**); Director of NERC Ocean Bottom Instrumentation Consortium (**Henstock**); Member of Expert Panel for UKRI Greenhouse Gas Removal Demonstrator programme, Strategic Priority Fund 2020 (**James**); Chair UKRI-NERC Climate Linked Atlantic Sector Science National Capability Advisory Group; Deputy Chair

Quinquennial Review of Cefas 2018, President of Challenger Society for Marine Science (**Mills**); NERC Science Board Member, NERC Cruise Programme Review group Member & Chair of Scoping Group of RoSES (Role of the Southern Ocean in the Earth System) NERC Strategic Research Programme (**Naveira Garabato**); Chair of NERC UK-IODP Programme Advisory Group (**Teagle**).

#### 4.8 Other indicators of wider influence

##### *Prizes and fellowships (examples):*

Regius Chair, Ocean Science (**Bryden**); 4 Royal Society Wolfson Merit awards (**Naviera-Garabato, Foster, Minshull, Wilson**); Honorary Fellow, Natural History Museum and Fellow Royal Society of Biology (**Mills**); Fellow of the American Geophysical Union (**Rohling**), Fellow Royal Society of Biology and Marine Biological Association of the UK (**Hauton**); Elected Member, Academia Europaea (**Sims**); Coke Medal, Geological Society London (**McNeill**); Fellowships Challenger Society for Marine Science (**Goodwin, Moore**); NERC IRFs (**Annett, Ward** (declined)), Royal Society Fellowships (**Coggon, Inglis, Ward**); Scientific Associate, Natural History Museum (**Copley**); Honorary Fellowship - British Antarctic Survey (**Naveira-Garabato**); Fellow Geochemical Society and Fellow European Society of Geochemistry (**Palmer**); Fellow of the Alan Turing Institute (**Gernon**); Ecological Society of America's 2019 Innovations in Sustainability Science Award (**Solan**); European Association of Geochemistry Early Career Science Ambassador Program (**Inglis**); Zoological Society of London Marsh Award for Marine and Freshwater Conservation (**Sims**).

##### *Journal review and Editorial boards:*

All SOES research staff regularly review for leading international journals and we provide members of editorial boards for a diverse range of journals (Figure 7).

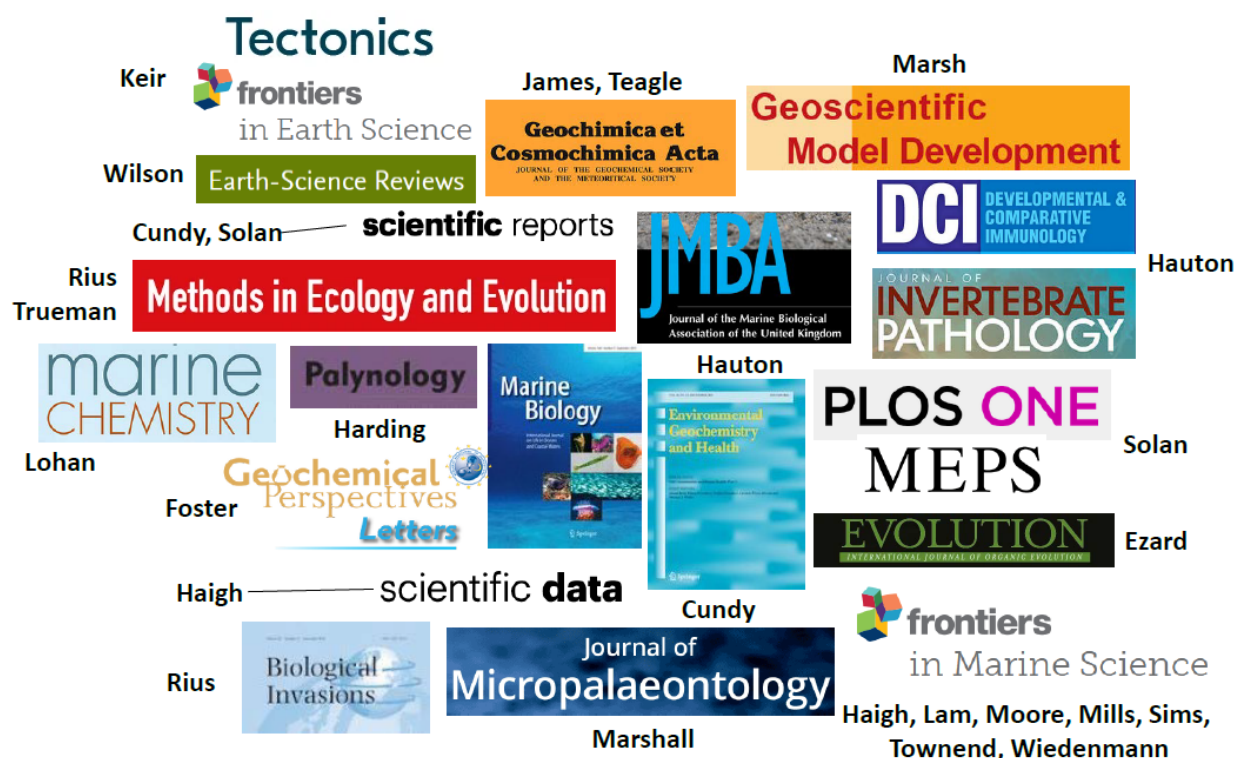


Figure 7. Editorial board membership for SOES staff

*Keynote lectures:*

>70% of SOES staff have delivered international invited keynote lectures, including: the 2014 European Association of Geochemistry Distinguished Lecturer (**James**), 5th International Whale Shark Conference, Exmouth, Australia and International Netherlands Annual Ecology Meeting (**Sims**); The International Liege Colloquium (**Solan**); Paläontologische Gesellschaft (**Marshall**); International Conference on Paleoceanography (**Bohaty**); International Symposium on Aquatic Animal Health and Epidemiology for Sustainable Asian Aquaculture (**Hauton**); Spring Symposium, Australian Earth Science Convention (**Gernon**); European Marine Science Educators Association and Royal Society of Biology Education Awards (**Copley**); 31st International Conference of the Society for Environmental Geochemistry and Health (**Cundy**); 8th Geochemistry symposium (**Palmer**); Ocean drilling Sumatra subduction zone meeting (**McNeill**); International Energy Agency Greenhouse Gas R&D Programme 4th International Workshop on Offshore Geologic CO<sub>2</sub> Storage (**Bull**); and multiple invited talks and keynotes at Gordon Research Conferences (**Lam, Minshull, Moore, Naviera-Garabato, Ward, Wiedenmann**), AGU meetings (**Foster, Goodwin, Keir, McNeill, Minshull**) and Goldschmidt (**Foster, Gernon, Lam, Moore**).